

# Evidence for single top quark production at DØ

Arán García-Bellido

*Department of Physics, University of Washington,  
Seattle, WA 98195, USA*



The results of the first analysis to show evidence for production of single top quarks are presented. Using  $0.9 \text{ fb}^{-1}$  of data collected with the DØ detector at the Fermilab Tevatron, the analysis is performed in the electron+jets and muon+jets decay modes, taking special care in modeling the large backgrounds, applying a new powerful  $b$ -quark tagging algorithm and using three multivariate techniques to extract the small signal in the data. The combined measured production cross section is  $4.8 \pm 1.3 \text{ pb}$ . The probability to measure a cross section at this value or higher in the absence of a signal is 0.027%, corresponding to a 3.5 standard deviation significance.

## 1 Introduction

The top quark is very special fermion: it is by far the heaviest elementary particle discovered so far. Its large mass gives it a prominent role in the mechanism of electroweak symmetry breaking, since the Higgs boson coupling to fermions is proportional to their mass, and hence top quarks and Higgs bosons have a coupling strength of order unity. Top quarks also decay before they hadronize and thus pass their kinematic properties to the decay products, that can be then used to study the nature of “bare” quarks. The study of this elusive quark has provided us with some new insights into its properties recently, like its charge of  $2/3e$ , its dominant decay to a  $W$  boson and a bottom quark, and its production cross section and mass, these last two being measured with ever increasing precision since its discovery.

Top quarks were first observed produced in  $t\bar{t}$  pairs via the strong interaction at the Tevatron collider in 1995. In the SM, top quarks are also expected to be produced via the exchange of a  $W$  boson in  $s$ - or  $t$ -channel. The final state in these channels thus consists of one “single” top quark together with a  $b$  quark in the  $s$ -channel ( $tb$ ) and an additional light quark in the  $t$ -channel ( $tqb$ ). Single top quarks can also be produced in association with a  $W$  boson ( $tW$ ), but the cross

section for this process at the Tevatron is very small and will be ignored here. The next-to-leading order prediction for the  $s$ -channel single top quark cross section is  $\sigma(p\bar{p} \rightarrow tb + X) = 0.88 \pm 0.11$  pb, and for the  $t$ -channel process, the prediction is  $\sigma(p\bar{p} \rightarrow tqb + X) = 1.98 \pm 0.25$  pb<sup>1</sup>.

Both the CDF and D $\emptyset$  collaborations have performed searches for this process in the past<sup>2</sup>. In Run II, the best published 95% C.L. upper limits are  $\sigma(p\bar{p} \rightarrow tb + X) < 6.4$  pb and  $\sigma(p\bar{p} \rightarrow tqb + X) < 5.0$  pb<sup>3</sup>. The analysis presented here, described in more detail in Ref.<sup>4</sup>, draws many techniques and experience from the previous D $\emptyset$  analyses, where it was made clear that multivariate techniques are necessary to be sensitive to the SM production cross section with limited data statistics.

## 2 Event selection

The data used in this search was collected from 2002 to 2005 with triggers that required an electron or a muon and at least one jet. The average trigger efficiency for e+jets events is 86% and 87% in the  $t$ - and  $s$ -channels, and for  $\mu$ +jets, 82% and 87% in  $t$ - and  $s$ -channels signal samples respectively. Events are required to have exactly one isolated electron (muon) with  $p_T > 15$  GeV (18 GeV) within  $|\eta| < 1.1$  (2.0), and  $\cancel{E}_T > 15$  GeV. Events are also required to contain two, three or four jets, using a cone algorithm with radius  $\mathcal{R} = \sqrt{(\Delta y)^2 + (\Delta\phi)^2} = 0.5$  (where  $y$  is rapidity and  $\phi$  is azimuthal angle) to cluster energy deposits in the calorimeter. The leading jet has  $p_T > 25$  GeV and  $|\eta| < 2.5$ , the second leading jet has  $p_T > 20$  GeV and  $|\eta| < 3.4$ , and subsequent jets have  $p_T > 15$  GeV and  $|\eta| < 3.4$ .

The selection requirements described above achieve a summed signal to background ratio of around 1:180, with an acceptance of around 5.0% and 4.5% for  $s$ - and  $t$ -channel events respectively. To enhance the signal content of the selection, at least one jet in the event is required to be identified as a  $b$ -quark jet. A neural network<sup>5</sup> has been used to identify jets originating from long-lived  $b$  hadrons. The variables used to identify such jets rely on the presence and characteristics of a secondary vertex and tracks with high impact parameters inside the jet. These variables are, ranked in order of separation power: (i) decay length significance of the Secondary Vertex Tagger (SVT); (ii) weighted combination of the tracks' IP significances; (iii) JLIP probability (that the jet originates from the primary vertex based on the Jet Lifetime Probability algorithm); (iv)  $\chi^2$  per degree of freedom of the SVT secondary vertex; (v) number of tracks used to reconstruct the secondary vertex; (vi) mass of the secondary vertex; and (vii) number of secondary vertices found inside the jet. For a 0.5% light-jet (mis)tag rate, we obtain a 50% average tag rate in data for  $b$  jets with  $|\eta| < 2.4$ .

By requiring events to have at least one  $b$ -tagged jet, the signal to background ratio is enhanced to 1:22 on the sum of all channels, and the most sensitive channel, with two jets and one  $b$ -tagged jet, reaches a signal to background ratio of 1:10. The acceptance after  $b$ -tagging is reduced to 3.2% in the  $s$ -channel and 2.1% in the  $t$ -channel. The final event yields after  $b$ -tagging are given in Table 1, shown separated only by jet multiplicity. Figure 1 shows the data-background agreement in six basic distributions for all the channels combined.

## 3 Background normalization and agreement with data

Looking at Tab. 1, it is evident that if we are to reliably extract such a small signal from such large backgrounds (around 62 expected signal events from a total of 1,398 data events, where the error on the total background prediction is larger than the expected signals) we need to make sure the backgrounds are properly modeled in both their kinematics and overall normalization.

The  $t\bar{t}$  background is normalized to the integrated luminosity times the predicted  $t\bar{t}$  cross section of  $6.8^{+0.6}_{-0.5}$  pb<sup>6</sup>. The  $W$ +jets background, together with the multijet background, is

Table 1: Numbers of expected and observed events in  $0.9 \text{ fb}^{-1}$  for  $e$  and  $\mu$ , 1  $b$  tag and 2  $b$  tag channels combined. The total background uncertainties are smaller than the component uncertainties added in quadrature because of anticorrelation between the  $W+\text{jets}$  and multijet backgrounds resulting from the background normalization procedure.

Source	2 jets	3 jets	4 jets
$tb$	$16 \pm 3$	$8 \pm 2$	$2 \pm 1$
$tqb$	$20 \pm 4$	$12 \pm 3$	$4 \pm 1$
$t\bar{t} \rightarrow \ell\ell$	$39 \pm 9$	$32 \pm 7$	$11 \pm 3$
$t\bar{t} \rightarrow \ell+\text{jets}$	$20 \pm 5$	$103 \pm 25$	$143 \pm 33$
$Wb\bar{b}$	$261 \pm 55$	$120 \pm 24$	$35 \pm 7$
$Wc\bar{c}$	$151 \pm 31$	$85 \pm 17$	$23 \pm 5$
$Wjj$	$119 \pm 25$	$43 \pm 9$	$12 \pm 2$
Multijets	$95 \pm 19$	$77 \pm 15$	$29 \pm 6$
Total background	$686 \pm 41$	$460 \pm 39$	$253 \pm 38$
Data	697	455	246

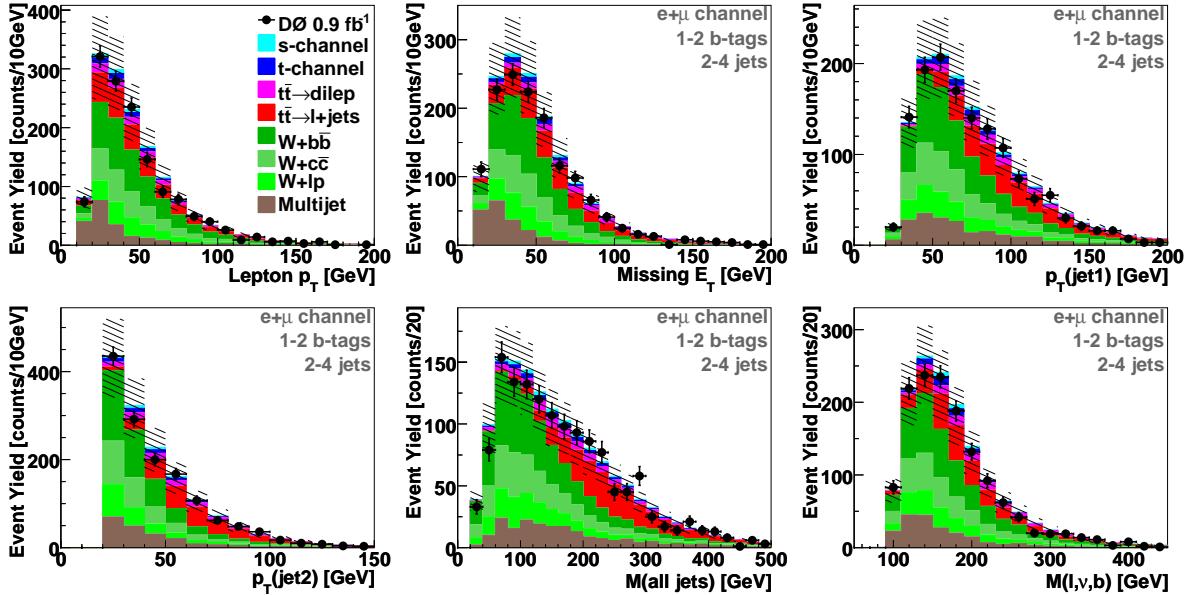


Figure 1: Data-background agreement distributions for all channels combined for the lepton  $p_T$ ,  $\cancel{E}_T$ , leading jet  $p_T$ , second leading jet  $p_T$ , the invariant mass of all jets, and the invariant mass of the reconstructed  $W$  together with the  $b$ -tagged jet. The hashed bands show the  $\pm 1$  standard deviation uncertainty on the background.

normalized to the data in each channel (defined by lepton flavor and jet multiplicity) before  $b$ -tagging.

A second normalization to data is performed in order to determine how much of the total  $W+\text{jets}$  sample is actually made of heavy-flavor jets, i.e. the fraction of  $Wb\bar{b}$  and  $Wc\bar{c}$  in the total  $W+\text{jets}$  sample.  $Wc+\text{jets}$  is included in our model together with other  $W+\text{light-quark}$  jets, i.e.: inside  $Wjj$  in Tab. 1. The heavy-flavor fraction is determined in our selected data on those events in which the neural network  $b$ -tagger fails to find a  $b$  jet of the required quality. This sample of events is not used for the signal measurement and has approximately the same heavy-flavor composition as the signal sample. We find that a constant scale factor of  $1.5 \pm 0.45$  applied to the  $Wb\bar{b}$  and  $Wc\bar{c}$  components is necessary to achieve a good description of the data. The uncertainty assigned to this factor covers the expected dependence on event kinematics and the assumption that the scale factor is the same for  $Wb\bar{b}$  and  $Wc\bar{c}$ .

This constant heavy-flavor scale factor which absorbs higher order effects <sup>7</sup>, was found to give overall a very good description of the data. It was checked that the most sensitive variables had well described shapes, specifically those distributions expected to suffer the largest shape dependence from higher order corrections, like the invariant mass of the two leading jets and the  $p_T$  of the  $b$ -tagged jet. Two control samples, one enriched in  $W+\text{jets}$  events and the other in  $t\bar{t}$  events, were also used to check for shape disagreements in the background model description of the data, and overall good agreement was found.

#### 4 Systematic errors

The dominant contributions to the uncertainties on the backgrounds come from: normalization of the  $t\bar{t}$  background (18%), which includes a term to account for the top quark mass uncertainty; normalization of the  $W+\text{jets}$  and multijet backgrounds to data (17–27%), which includes the uncertainty on the heavy-flavor fraction of the model; and the  $b$ -tagging probabilities (12–17% for double-tagged events). The uncertainty on the integrated luminosity is 6%; all other sources contribute at the few percent level. The uncertainties from the jet energy scale corrections and the  $b$ -tagging probabilities affect both the shape and normalization of the simulated distributions.

The 30% error assigned to the heavy-flavor fraction is by far the dominant uncertainty in the final cross section measurement. Its impact is nevertheless not directly 30% because it only affects two sources of the background (before  $b$ -tagging is applied) and it gets further reduced when taking into account the first normalization of  $W+\text{jets}$  and QCD to data, such that in the end, the total uncertainty on the sum of  $W+\text{jets}$  and QCD yields is between 17 and 27% (depending on the channel), including the heavy-flavor factor uncertainty.

#### 5 Final separation methods and cross section measurements

Three separate multivariate techniques have been employed in DØ to extract the signal from the data: Boosted Decision Trees <sup>8</sup>, Matrix Elements discriminants <sup>9</sup> and Bayesian Neural Networks <sup>10</sup>. The output distributions in the most sensitive channel, shown in Fig. 2 for the three methods, also demonstrate good overall agreement between data and background.

In order to extract the maximum information from the discriminant outputs, instead of cutting on the outputs and counting events, the full distributions are fed into a Bayesian statistical analysis to measure the single top quark production cross section. The expected and observed cross section results are summarized in Fig 3. The uncertainties include statistical and systematic components combined. The data statistics contribute 1.2 pb to the total 1.4 pb uncertainty on the  $t\bar{b}+t\bar{q}b$  cross section for the DT analysis. The significance is measured re-running the analysis on 70,000 pseudo-datasets generated with all the uncertainties on the background model taken into account, but including only background sources. Thus we obtain the probability for

the background-only hypothesis to fluctuate up to give the measured (or SM) value of the  $tb+tqb$  cross section or greater.

To verify the kinematics of the selected events in the most discriminant region of the DT outputs, the  $t$ -channel characteristic distribution of  $Q(\text{lepton}) \times \eta(\text{un>tagged leading jet})$  is plotted in different slices of the DT output in Fig. 4. Requiring higher DT outputs clearly selects more signal-like data and the distinct asymmetric signal shape can be seen taking form.

The three analyses are highly correlated since they all use the same signal and background models and data, with almost the same systematic uncertainties. The correlation between the three methods has been measured in fake pseudo data-sets (which include the systematic uncertainties on our background model), with the SM single top cross section. The best linear unbiased estimator (BLUE) has been applied to the three measured values and their correlations to give a combined measured cross section of  $\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 4.8 \pm 1.3 \text{ pb}$ , which corresponds to a significance of 0.027% (or 3.5 standard deviations).

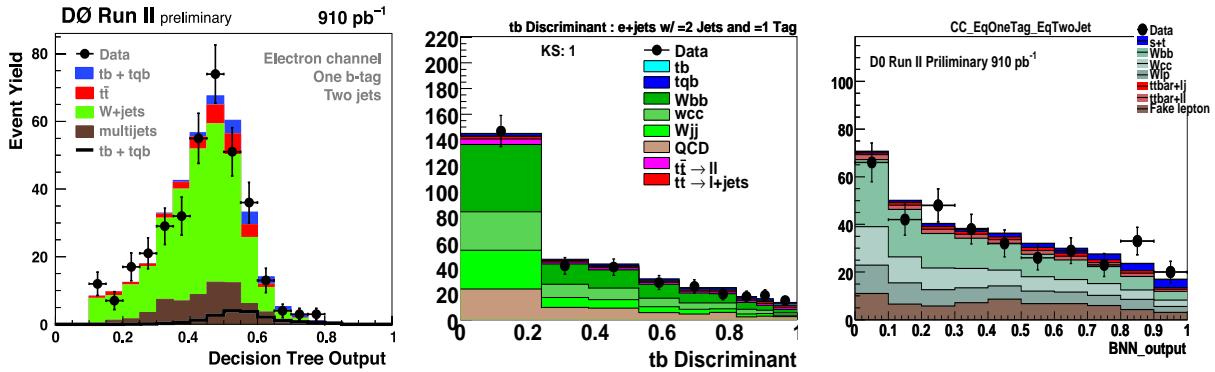


Figure 2: Output distributions in the electron channel with two jets, one of them  $b$ -tagged, for the Decision Tree discriminant (left), for the Matrix Element  $tq$  discriminant (center), and for the Bayesian Neural Net discriminant (right).

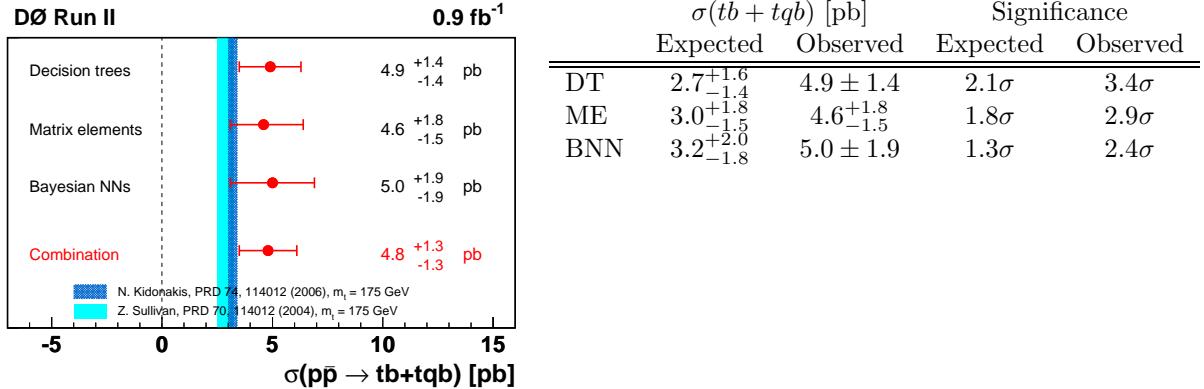


Figure 3: The observed results including the combination (left); and the expected and observed cross sections and significance for the three different multivariate analyses (right).

## 6 Measurement of $|V_{tb}|$

We use the decision tree measurement of the  $tb+tqb$  cross section to derive a first direct measurement of the strength of the  $V - A$  coupling  $|V_{tb}f_1^L|$  in the  $Wtb$  vertex, where  $f_1^L$  is an arbitrary left-handed form factor<sup>11</sup>. We measure  $|V_{tb}f_1^L| = 1.3 \pm 0.2$ . This measurement assumes  $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$  and a pure  $V - A$  and CP-conserving  $Wtb$  interaction. Assuming in addition that  $f_1^L = 1$ , we obtain  $0.68 < |V_{tb}| \leq 1$  at 95% C.L.. These measurements make no assumptions about the number of quark families or CKM matrix unitarity.

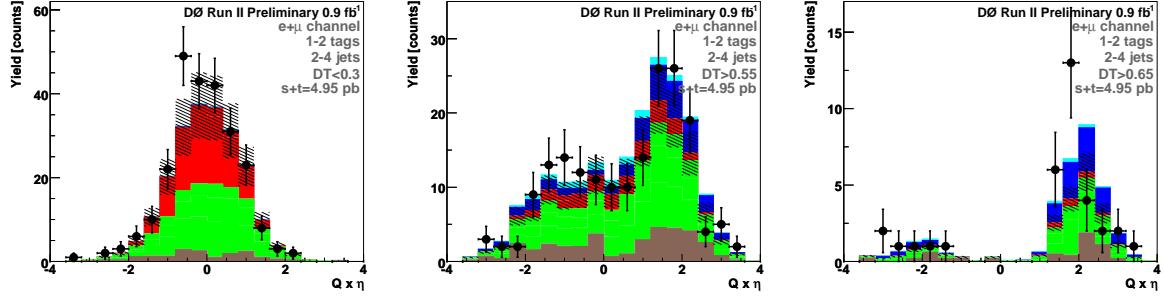


Figure 4: Data-background distribution of  $Q(\text{lepton}) \times \eta(\text{un-tagged leading jet})$  for three different cuts on the  $tb + tqb$  DT output: low ( $DT < 0.3$ , left plot), high ( $DT > 0.55$ , middle plot), and very high ( $DT > 0.65$ , right plot).

## 7 Summary

To summarize, we have performed a search for single top quark production using  $0.9 \text{ fb}^{-1}$  of data collected by the DØ experiment at the Tevatron collider. We find an excess of events over the background prediction in the high discriminant output region from three analyses and interpret it as evidence for single top quark production. The excess has a combined significance of 3.5 standard deviations and the combined first measurement of the single top quark cross section is:  $\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 4.8 \pm 1.3 \text{ pb}$ .

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